Digital Elevation Model for Lahaina, Hawaii: Procedures, Data Sources and Analysis

Prepared for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research by the NOAA National Geophysical Data Center (NGDC)
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1. INTRODUCTION

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed a bathymetric–topographic digital elevation model (DEM) of Lahaina, Hawaii (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). The 1/3 arc-second[1] coastal DEM will be used as input for the MOST (Method of Splitting Tsunami) model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) and will be used for tsunami inundation modeling, as part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Lahaina DEM.

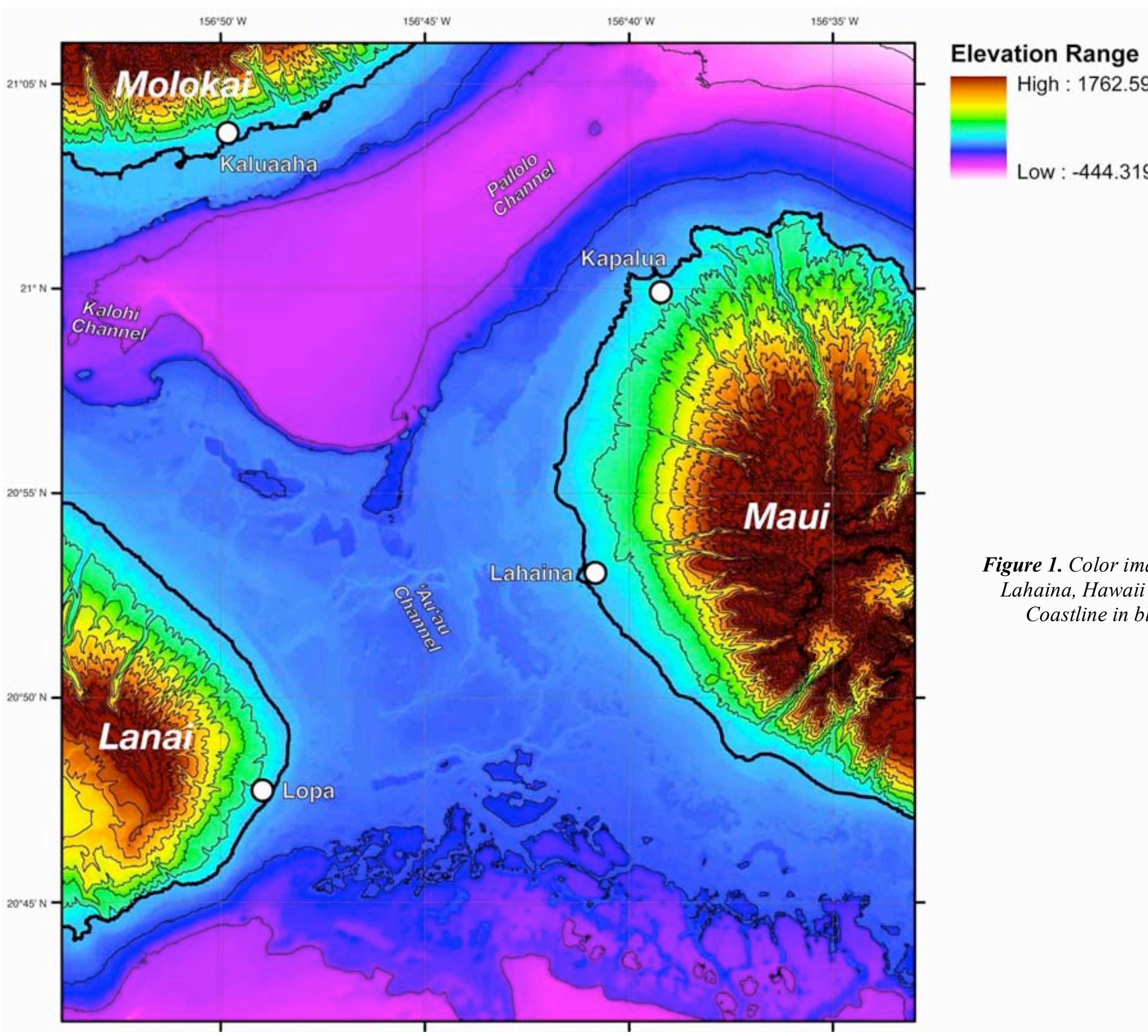

Figure 1. *Color image of the Lahaina, Hawaii region. Coastline in black.*

1. The Lahaina DEM is built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Lahaina, Hawaii (20°52′ N, 156°41′ W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.63 meters.

2. Study Area

The Lahaina DEM covers the coastal region centered on the western coast of the island of Maui, Hawaii, and the marine channels between Maui, Lanai and Molokai, including the communities of Lahaina and Kapalua, Maui, Lopa, Lanai, and Kaluaaha, Molokai (Fig. 1). Development in the coastal zone in these popular tourist destinations has modified local morphology, especially in boat harbors (e.g., Fig 2).

The islands of Hawaii have been created by shield-building volcanoes, whose low-viscosity lava flows often reach the coast. The marine channels between the islands exhibit significant morphologic relief (Fig. 1), reflecting alternation between living and drowned coral reefs built atop submarine volcanic material (see http://geopubs.wr.usgs.gov/i-map/i2809/ for further information).

Figure 2. *Aerial image of Lahaina Harbor (http://www.soest.hawaii.edu/coasts/data/maui/obliquephoto.html).*

3. Methodology

The Lahaina DEM was developed to meet PMEL specifications (Table 1), based on input requirements for the MOST inundation model. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System 1984 (WGS84) and Mean High Water (MHW), for modeling of "worst-case scenario" flooding, respectively. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the Lahaina, Hawaii DEM.

Grid Area	Lahaina, Hawaii
Coverage Area	156.55º to 156.9º W; 20.7º to 21.1º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI ASCII raster grid

3.1 Data Sources and Processing

Shoreline, bathymetric and topographic digital datasets (Fig. 3) were obtained from several U.S. federal agencies, including: NOAA's National Ocean Service (NOS) and Coastal Services Center (CSC); the U.S. Geological Survey (USGS); the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX); and the National Geospatial-Intelligence Agency (NGA). The data were collected by numerous methods, in different terrestrial environments, and at various scales and resolutions. Datasets were assessed for quality and accuracy both within each dataset, and between datasets to ensure consistency and gradual topographic transitioning along the edges of datasets. Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to WGS84 horizontal datum and to convert into ESRI (http://www.esri.com/) ArcGIS shape files. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets; NGDC's GEODAS software (http://www.ngdc.noaa.gov/mgg/geodas/) was used to manually edit large xyz datasets. Vertical datum transformations to MHW were also accomplished using FME, based upon data from a NOAA tide station on Maui, as no VDatum model software (http://nauticalcharts.noaa.gov/csdl/vdatum.htm) was available for this area.

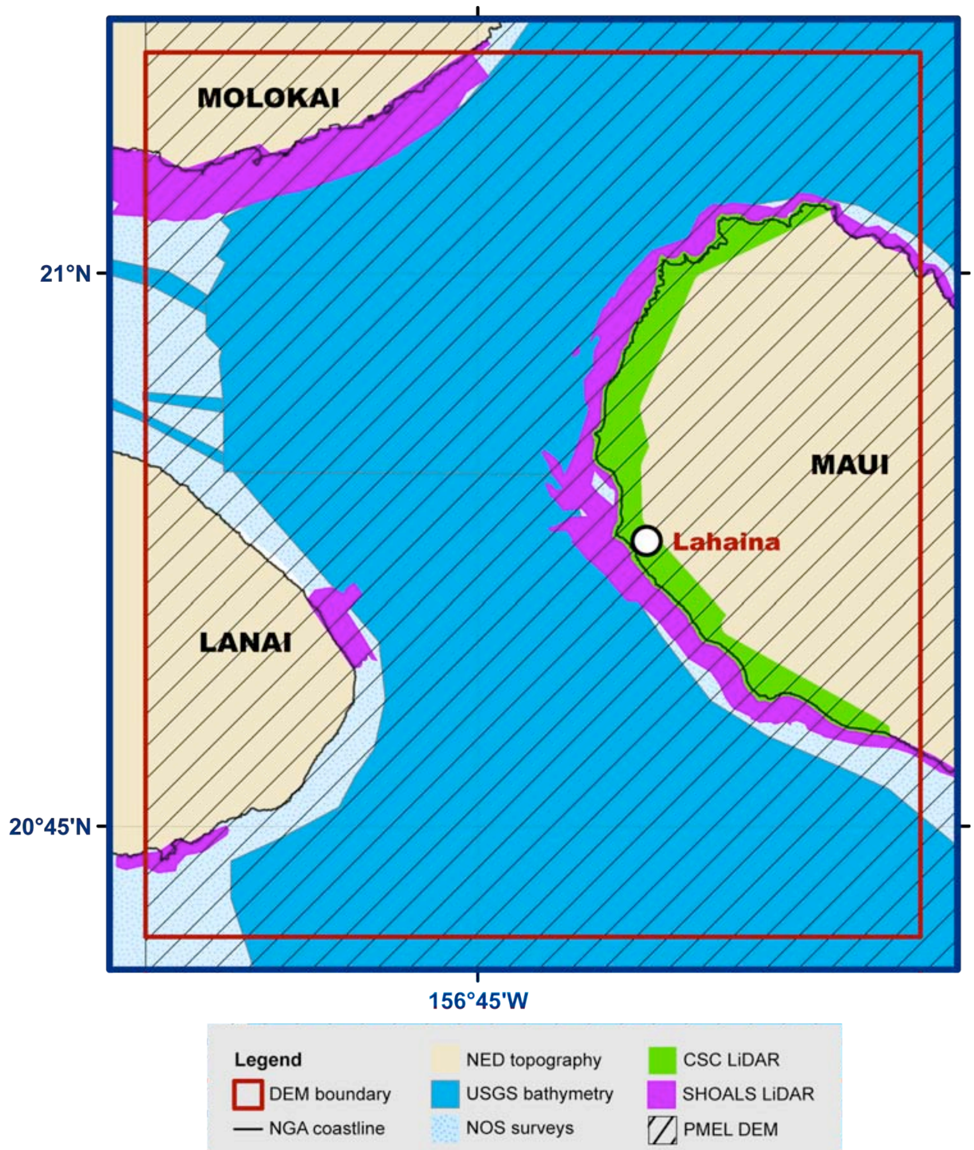

Figure 3. *Source and coverage of datasets used to compile the Lahaina DEM.*

3.1.1 Shoreline

One digital coastline dataset of the Lahaina region was used in building the Lahaina DEM: the National Geospatial-Intelligence Agency (NGA; Table 2).

Table 2. Shoreline datasets used in compiling the Lahaina DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
NGA	1998 to 2002	MHW shoreline	50 meters	WGS84	MHW

1) NGA Global Imagery-Derived Shoreline

The NGA Global Imagery-Derived Shoreline is an unclassified vector dataset generated by Earth Satellite Corporation (EarthSat) of Rockville, Maryland for NGA, under contract to Boeing in 2004. The shoreline is referenced to MHW and constructed from consistently orthorectified Landsat TM satellite imagery (GeoCover Ortho), acquired between 1998-2002 for NASA under the Global Land Mapping Program (GLMP). NDVI and SWIR models were used to define the landward extent of inundation (i.e., MHW). Independently verified positional accuracy for the source product (GeoCover Ortho) is consistently better than 50m root mean square (RMS) error.

The NGA coastline was mostly consistent with coastal topographic and bathymetric LiDAR surveys, though it was modified in places to match those datasets. Piers, docks, and other manmade structures were also present in the coastline, which had to be deleted. The NGA coastline was converted to point data for use as a coastal buffer for the bathymetric pre-surfacing algorithm (see Section 3.3.2) to ensure that interpolated bathymetric values reached "zero" at the coast. It was also used to clip USGS NED topographic DEMs, which contain elevation values, typically zero, over the open ocean (Section 3.1.3).

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Lahaina DEM include 38 NOS hydrographic surveys, a USGS multibeam survey of the channels between the islands, and JALBTCX SHOALS bathymetric LiDAR surveys along the coasts (Table 3; Fig. 4).

Table 3. Bathymetric datasets used in compiling the Lahaina DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1931 to 1984	Hydrographic survey soundings	Ranges from 10 m to 1 km (varies with scale of survey, depth, traffic, and probability of obstructions)	Early Hawaiian Island or Old Hawaiian	MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
USGS	1998	DEM	20 meters	NAD83, UTM Zone 4	MSL	http://walrus.wr.usgs.gov/pacmaps/mi_index.html
USGS	1998	multibeam	~1 meter	WGS84 geographic	MSL	
JALBTCX	1999 to 2000	SHOALS LiDAR	averages 5 to 10 meters	WGS84 geographic	MLLW	http://shoals.sam.usace.army.mil/hawaii/pages/Hawaii_Data.htm

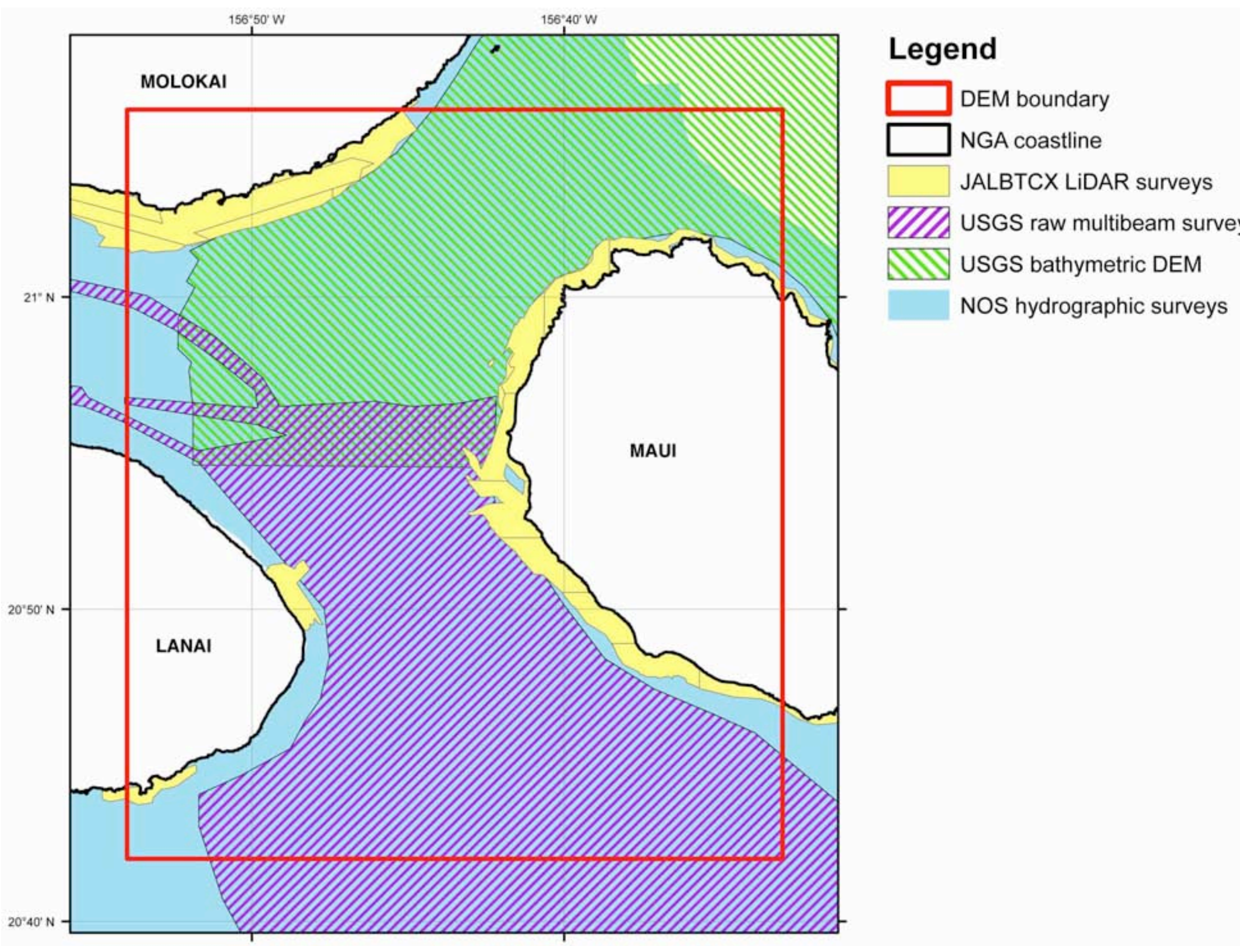

Figure 4. *Source and coverage of bathymetric datasets used to compile the Lahaina DEM.*

1) NOS hydrographic survey data

A total of 38 NOS hydrographic surveys conducted between 1931 and 1984 were utilized in developing the Lahaina DEM (Table 4; Fig. 5). The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to either Early Hawaiian Island or Old Hawaiian datums.

Data point spacing for the NOS surveys varied by collection date. In general, earlier surveys had greater point spacing than more recent surveys. All surveys were extracted from NGDC's online NOS hydrographic database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original, digitized vertical datum and NAD83 horizontal datum (Table 4). The data were then converted to WGS84 and MHW using FME software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com). The surveys were subsequently clipped to a polygon 0.05 degrees (~10%) larger than the Lahaina DEM area to support data interpolation along grid edges.

After converting all NOS survey data to MHW (see Section 3.2.1), the data were displayed in ESRI ArcMap and reviewed for digitizing errors against scanned original survey smooth sheets and compared to coastal topographic LiDAR and NED data, JALBTCX coastal bathymetric LiDAR data, the NGA coastline, NOAA nautical charts, and *Google Earth* satellite imagery.

Table 4. Digital NOS hydrographic surveys used in compiling the Lahaina DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H05290	1931	20,000	mean lower low water	early Hawaiian Island
H05297	1931/32	40,000	mean lower low water	early Hawaiian Island
H05298	1932	5,000	mean lower low water	early Hawaiian Island
H05310	1931	20,000	mean lower low water	early Hawaiian Island
H05311	1931	20,000	mean lower low water	early Hawaiian Island
H05337	1931	20,000	mean lower low water	early Hawaiian Island
H05338	1931	5,000	mean lower low water	early Hawaiian Island
H05339	1932	100,000	mean lower low water	early Hawaiian Island
H08576	1961	10,000	mean lower low water	old Hawaiian
H08577	1961	10,000	mean lower low water	early Hawaiian Island
H08578	1961	10,000	mean lower low water	early Hawaiian Island
H08579	1961	10,000	mean lower low water	early Hawaiian Island
H08580	1961	10,000	mean lower low water	old Hawaiian
H08581	1961	5,000	mean lower low water	early Hawaiian Island
H08582	1961	5,000	mean lower low water	old Hawaiian
H08583	1961/62	40,000	mean lower low water	old Hawaiian
H08677	1962	40,000	mean lower low water	early Hawaiian Island
H08678	1962	20,000	mean lower low water	old Hawaiian
H08679	1962	20,000	mean lower low water	old Hawaiian
H08680	1962	10,000	mean lower low water	old Hawaiian
H08683	1962	10,000	mean lower low water	early Hawaiian Island
H08685	1962	5,000	mean lower low water	early Hawaiian Island
H08828	1965	5,000	mean lower low water	old Hawaiian
H08831	1965	10,000	mean lower low water	old Hawaiian
H08832	1965	10,000	mean lower low water	old Hawaiian
H08833	1965	40,000	mean lower low water	early Hawaiian Island
H08834	1965	20,000	mean lower low water	old Hawaiian
H08835	1965	10,000	mean lower low water	old Hawaiian
H08881	1965	5,000	mean lower low water	old Hawaiian
H08882	1965	10,000	mean lower low water	old Hawaiian
H08886	1966	10,000	mean lower low water	old Hawaiian
H08889	1966	10,000	mean lower low water	early Hawaiian Island
H08919	1966/67	10,000	mean lower low water	early Hawaiian Island
H08998	1968	10,000	mean lower low water	early Hawaiian Island
H09130	1971/72	40,000	mean lower low water	early Hawaiian Island
H09611	1976	20,000	mean lower low water	early Hawaiian Island

H10126	1984	2,500	mean lower low water	early Hawaiian Island
H10169	1984	2,500	mean lower low water	old Hawaiian

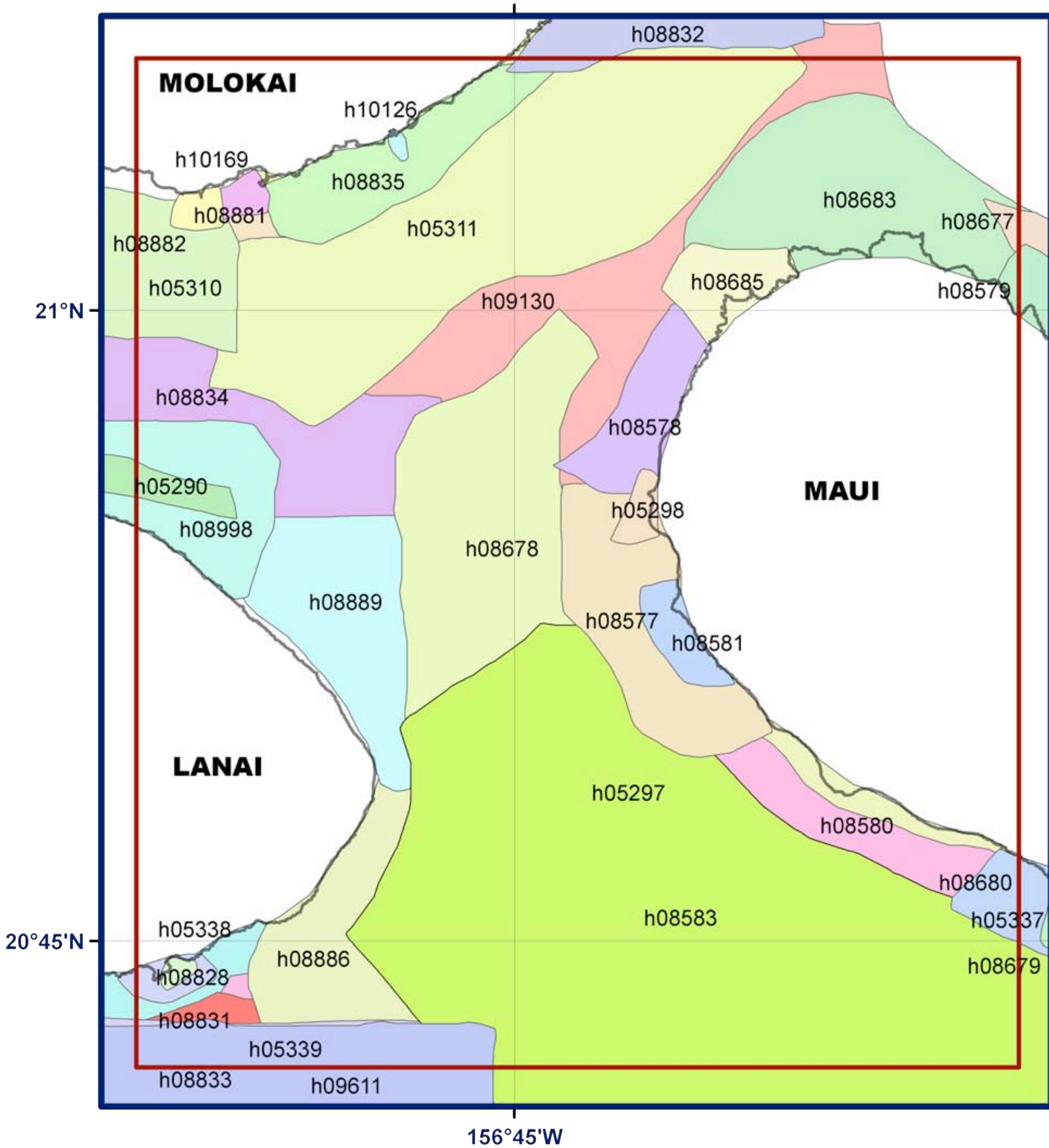

Figure 5. *Digital NOS hydrographic survey coverage in the Lahaina region. DEM boundary in red, NGA coastline in gray.*

2) USGS multibeam surveys

The USGS conducted high-resolution multibeam swath sonar surveys around the Hawaiian Islands in 1998. These data were processed by USGS, with bathymetric DEMs posted online for public access. The DEM of the Maui survey (see Fig. 6), in the channels between Maui, Lanai, Kahoolawe, and Molokai was downloaded from the USGS web site (http://walrus.wr.usgs.gov/pacmaps/mi_index.html). It has a 20-meter cell size and is in NAD83, UTM Zone 4 coordinates. NGDC also obtained the raw multibeam sonar files—~1-meter resolution—for most of the USGS Hawaii surveys, with the exception of the Pailolo Channel between Maui and Molokai, which are presumed lost.

Comparison of a bathymetric grid of the multibeam data with the USGS DEM revealed that seafloor features were offset roughly 100 meters to the south in the DEM. Further comparison with coastal JALBTCX LiDAR data showed that the grid derived from the raw multibeam sonar data to be consistent with the coastal LiDAR data where the two datasets overlap to the southwest of Lahaina. NGDC chose to use the raw multibeam sonar data within ‘Au‘au Channel, and the USGS Maui DEM only in the northern region (Pailolo Channel) where the raw multibeam is not available.

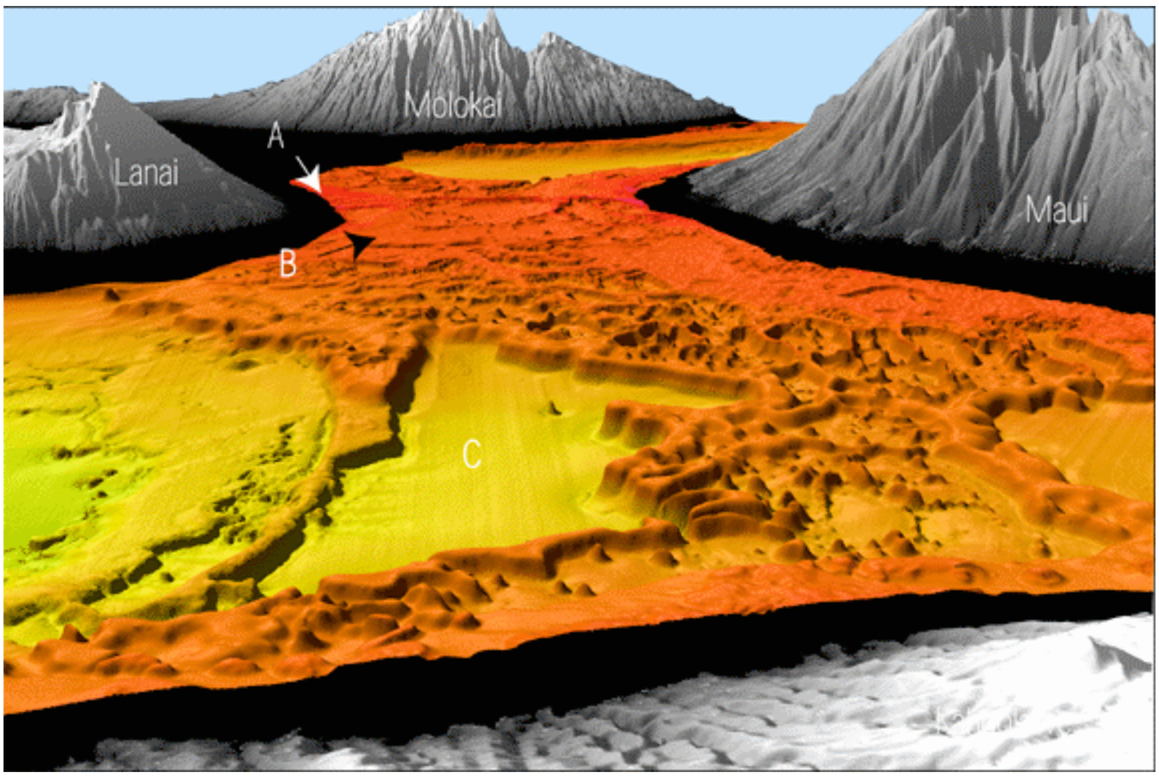

Figure 6. *Oblique view of the seafloor between the islands of Kahoolawe (foreground), Molokai, Lanai, and Maui. Image is derived from a DEM built from the USGS multibeam survey around Maui. The vertical exaggeration is 5 times. Image obtained from http://walrus.wr.usgs.gov/pacmaps/mi-fig1.html.*[2]

2. Oblique overview of the seafloor between Kahoolawe (foreground), Molokai (background), Lanai (left side), and Maui (right side). Distance between Lanai and Maui about 20 km. The sparse red regions between Lanai and Maui (A) are the present living reefs in water depths of less than 40 m, dark orange areas (B) are drown reef platforms and pinnacles in water depths between 50 and 85 m. Large basin in middle of view (C) is shown in more detail in Figs. 2 and 3. Maui is known to be subsiding about 2 mm/y under the load of the volcano, a rate that must have slowed with time. In addition, long-term sea level rises and falls at about 2 mm/y. The area between Lanai and Maui has filled with lava flows as the islands subsided and vertical growth of coral reefs kept pace with sea level fluctuations and island subsidence. Coral growth in the area between Lanai, Kahoolawe, and Maui has not kept pace with fluctuations in sea level, island subsidence, and lava-flow buildup, and is now drowned. The scale across the bottom of the image is10 km. The vertical exaggeration is 5x. [Extracted from web site.]

3) JALBTCX LiDAR surveys

High-resolution bathymetric LiDAR surveys of coastal Hawaii have been performed by Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX; Fig. 7). The data were collected using the SHOALS[3] (Scanning Hydrographic Operational Airborne Lidar Survey) system along the Maui coastline and parts of the Lanai and Molokai coasts. The LiDAR data have a horizontal accuracy of 3 meters, and a vertical accuracy of 15 cm. The surveys have point spacings of between 2 and 10 meters, and measure the seafloor down to about 40 meters depth.

Positive elevation values were present in the data, reflecting subaerial returns, and were excised by NGDC prior to building the Lahaina DEM. Some anomalous values were also present in bathymetric regions, which were also deleted.

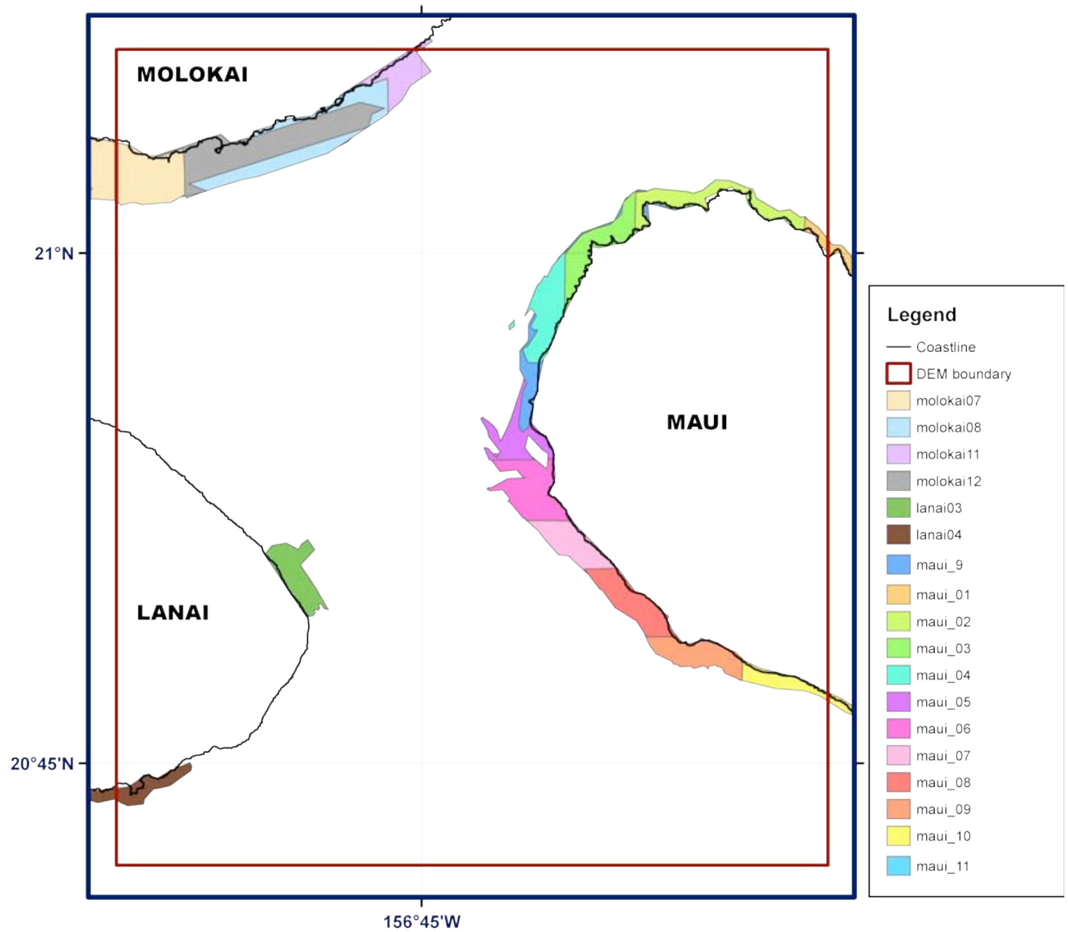

Figure 7. *Spatial coverage of JALBTCX SHOALS bathymetric LiDAR surveys in the Lahaina region.*

3. These data were collected by the SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system, which consists of an airborne laser transmitter/receiver capable of measuring 400 soundings per second. The system operates from a deHavilland DHC-6 Twin Otter flying at altitudes between 200 and 400 meters with a ground speed of about 100 knots. The SHOALS system also includes a ground-based data processing system for calculating acurate horizontal position and water depth. Lidar is an acronym for LIght Detection And Ranging. The system operates by emitting a pulse of light that travels from an airborne platform to the water surface where a small portion of the laser energy is backscattered to the airborne receiver. The remaining energy at the water's surface propogates through the water column and reflects off the sea bottom and back to the airborne detector. The time difference between the surface return and the bottom return corresponds to water depth. The maximum depth the system is able to sense is related to the complex interaction of radiance of bottom material, incident sun angle and intensity, and the type and quantity of organics or sediments in the water column. As a rule-of-thumb, the SHOALS system should be capable of sensing bottom to depths equal to two or three times the Secchi depth. [Extracted from metadata.]

3.1.3 Topography

Topographic datasets in the Lahaina region were obtained from NOAA's Coastal Services Center and the U.S. Geological Survey (Table 5; Fig. 8).

Table 5. Topographic datasets used in compiling the Lahaina DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
CSC Oahu/Maui Mapping Project	2005	topographic LiDAR DEM	~ 2 meters	NAD83, UTM Zone 4	Local Tidal Datum	
USGS	2001	NED 1/3 arc-second DEM	~10 m	NAD83 geographic	NAVD88 (meters)	http://ned.usgs.gov/

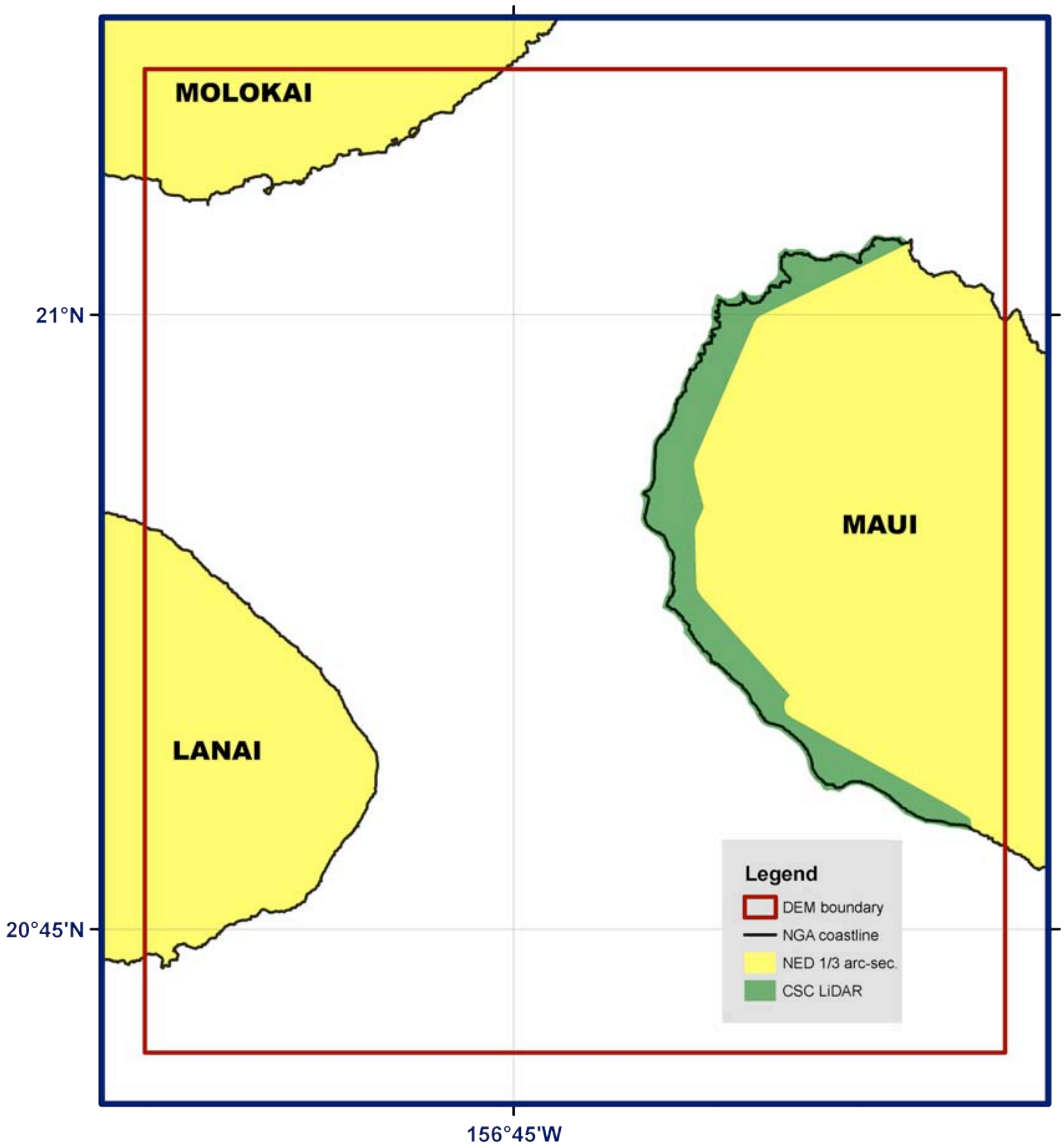

Figure 8. *Source and coverage of topographic datasets used in building the Lahaina DEM.*

1) CSC Topographic Mapping Project

NOAA's Coastal Services Center's (CSC) Coastal Remote Sensing Program funded coastal topographic LiDAR surveys on the Hawaiian Islands of Oahu and Maui. The Maui survey data were collected[4] in 2005 and processed to bare earth[5] by EarthData Aviation. CSC provided bare earth DEMs of the LiDAR data—2-meter cell size—to NGDC for use in building the Lahaina DEM. Evaluation of the DEMs revealed that buildings and other man-made features had been removed, though anomalous values within Lahaina Harbor appear to result from LiDAR returns from the ocean surface and moored vessels (Fig. 9). These values were removed by NGDC before building the Lahaina DEM.

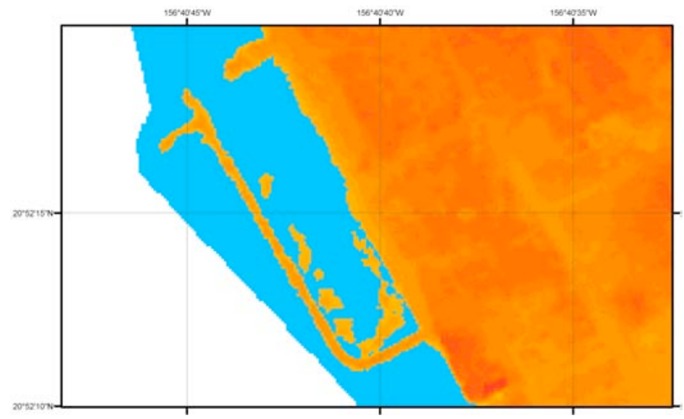

Figure 9. *Color image of the CSC bare-earth DEM in the vicinity of Lahaina Harbor. The DEM shows anomalous elevation values within the harbor that presumably result from moored vessels, as well as the ocean surface (blue).*

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4. EarthData Aviation was contracted by EarthData International to collect ALS-40 Lidar data over the west coast of Maui, Hawaii. The project site was flown on March 16th and 24th of 2005, using aircraft N806CP. Lidar data was captured using an ALS-40 Lidarsystem, including an inertial measuring unit (IMU) and a dual frequency GPS receiver. Lidar was obtained at an altitude of 762 meters (2,500 feet) above mean terrain, at an average airspeed of 130 knots. Sensor pulse rate was set at 20,000 Hz with a field of view of 25 degrees and a scan rate of 17 Hz. Average swath width of the collected raw lines is 337 meters. Lidar data was recorded in conjunction with airborne GPS and IMU; the stationary GPS receiver was positioned over a control point located at the airport. Recorded digital data was shipped via external hard drive to the production facility for processing. During airborne data collection, an additional GPS receiver was in constant operation over a published National Geodetic Survey (NGS) control point at Kahului Airport. The control point with designation OGG ARP 2 and PID AA3608, is "A" Order horizontal with Third Order Class II ellipsoid height. During the data acquisition, the receivers collected phase data at an epoch rate of 1 Hz. All GPS phase data was post processed with continuous kinematic survey techniques using "On the Fly" (OTF) integer ambiguity resolution. The GPS data was processed with forward and reverse processing algorithms. An adjustment was made to the ellipsoid height of the published point by Terrasurv to reflect Local Tidal Elevation. The results from each process, using the data collected at the airport, were combined to yield a single fixed integer phase differential solution of the aircraft trajectory. [Extracted from metadata.]

5. EarthData has developed a unique method for processing lidar data to identify and remove elevation points falling on vegetation, buildings, and other aboveground structures. The algorithms for filtering data were utilized within EarthData's proprietary software and commercial software written by TerraSolid. This software suite of tools provides efficient processing for small to large-scale, projects and has been incorporated into ISO 9001 compliant production work flows. The following is a step-by-step breakdown of the process. (1) Using the lidar data set provided by EarthData, the technician performs calibrations on the data set. (2) Using the lidar data set provided by EarthData, the technician performed a visual inspection of the data to verify that the flight lines overlap correctly. The technician also verified that there were no voids, and that the data covered the project limits. The technician then selected a series of areas from the data set and inspected them where adjacent flight lines overlapped. These overlapping areas were merged and a process which utilizes 3-D Analyst and EarthData's proprietary software was run to detect and color code the differences in elevation values and profiles. The technician reviewed these plots and located the areas that contained systematic errors or distortions that were introduced by the lidar sensor. (3) Systematic distortions highlighted in step 2 were removed and the data was re-inspected. Corrections and adjustments can involve the application of angular deflection or compensation for curvature of the ground surface that can be introduced by crossing from one type of land cover to another. (4) The lidar data for each flight line was trimmed in batch for the removal of the overlap areas between flight lines. The data was checked against a control network to ensure that vertical requirements were maintained. Conversion to the client-specified datum and projections were then completed. The lidar flight line data sets were then segmented into adjoining tiles for batch processing and data management. (5) The initial batch-processing run removed 95% of points falling on vegetation. The algorithm also removed the points that fell on the edge of hard features such as structures, elevated roadways and bridges. (6) The operator interactively processed the data using lidar editing tools. During this final phase the operator generated a TIN based on a desired thematic layers to evaluate the automated classification performed in step 5. This allowed the operator to quickly re-classify points from one layer to another and recreate the TIN surface to see the effects of edits. Geo-referenced images were toggled on or off to aid the operator in identifying problem areas. The data was also examined with an automated profiling tool to aid the operator in the reclassification. (7) The final DEM was written to an ESRI grid format (.flt). [Extracted from metadata.]

2) USGS NED topography

The U.S. Geological Survey (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provided complete 1/3 arc-second coverage of the Lahaina region[6]. Data are in NAD83 geographic coordinates and NGVD88 vertical datum (meters), and are available for download as raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys; it has been revised using data collected in 1999 and 2004.

The NED data included "zero" elevation values over the open ocean (Fig. 10), which were removed from the dataset before gridding. Non-zero values still remained over the open ocean, which were visually inspected and compared with NOAA nautical charts, the NGA coastline, and *Google Earth* satellite imagery. ESRI Arc Catalog was used to clip the data to the NGA coastline.

The NAVD88 vertical datum is established only for the North American mainland and has not been surveyed for Hawaii. The NED DEMs are therefore inferred to represent elevations relative to Mean Sea Level, not NAVD88.

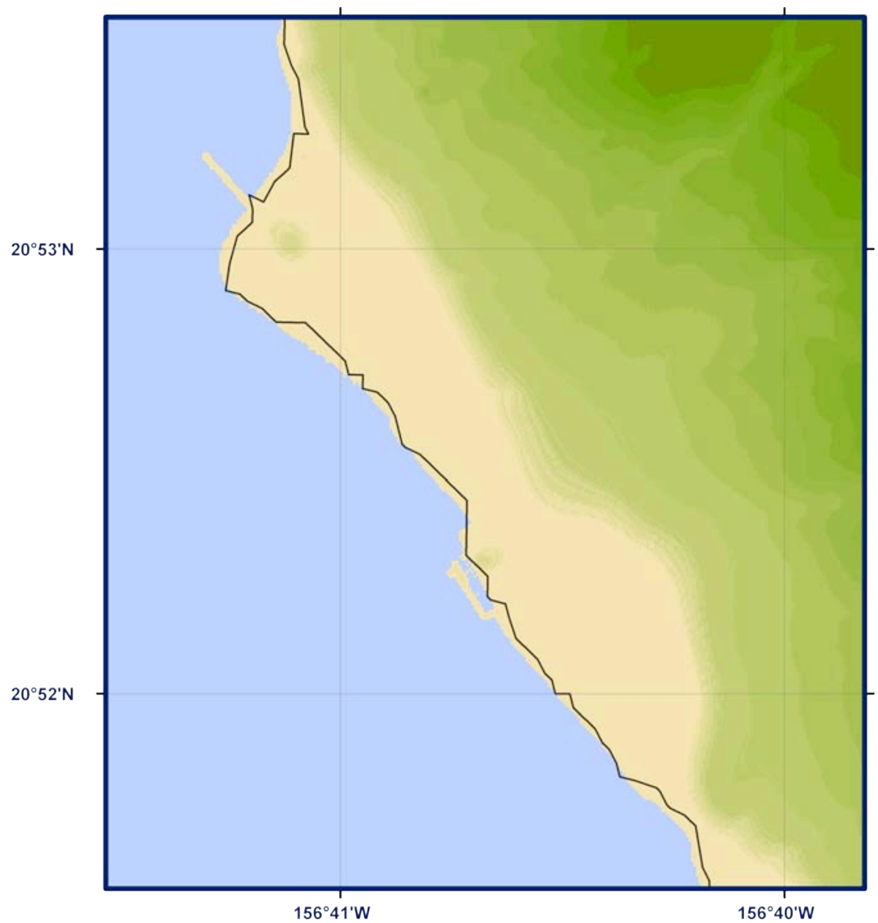

Figure 10. *Color image of the NED DEM in the vicinity of Lahaina. Blue represents "zero" values in the NED DEM over the open ocean. NGA coastline is shown in black.*

6. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD83, except for AK, which is NAD27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED website]

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Lahaina DEM were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean Sea Level (MSL), Local Tidal datum, and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW to provide the worst-case scenario for inundation modeling, using values measured at the NOAA tidal station at Kahului, Maui (#1615680; Table 6).

1) **Bathymetric data**

   The NOS hydrographic and JALBTCX LiDAR surveys were transformed from MLLW to MHW, using FME software, by adding a constant offset of -0.577 m. The USGS raw multibeam data and Maui DEM are inferred to be referenced to MSL and were shifted by adding a constant offset of -0.238 m.

2) **Topographic data**

   The USGS NED 1/3 arc-second DEMs were originally referenced to NAVD88, which is not defined in Hawaii: this dataset was inferred to be referenced to MSL. The CSC coastal LiDAR bare-earth DEMs were referenced to "Local Tidal" datum, which is undefined. They too are inferred to be referenced to MSL. Conversion to MHW, using FME software, was accomplished by adding tide-station derived constant offsets (Table 6).

Table 6. Relationship between Mean High Water and other vertical datums in the Lahaina region.*

Vertical datum	*Difference to MHW*
MSL+	-0.238
MLW	-0.478
MLLW	-0.577

* Datum relationships measured at tide station #1615680, Kahului, Maui.
\+ Topographic data referenced to Local Tidal datum or NAVD88 inferred to be equivalent to MSL.

3.2.2 Horizontal datum transformations

Datasets used to compile the Lahaina DEM were originally referenced to NAD83 geographic, NAD83 UTM Zone 4, or WGS84 geographic horizontal datums. The relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of WGS84 using FME software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shape files were checked in ESRI ArcMap for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- Presence of man-made structures and river banks in the NGA coastline dataset, which had to be removed.
- Inconsistencies between the NGA coastline dataset and bathymetric and topographic datasets. These inconsistencies are partly the result of lower resolution of the NGA coastline.
- Data values over the open ocean and rivers in the NED and CSC bare-earth DEMs. The DEMs required automated clipping to the NGA coastline.
- Offset of bathymetric features between the USGS raw multibeam data and the corresponding DEM built by USGS. The raw multibeam data were more consistent with overlapping JALBTCX LiDAR bathymetry along coastal Maui.

3.3.2 Gridding of raw USGS multibeam bathymetric data

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to grid the raw multibeam sonar files from the USGS survey of the channel between Maui and Lanai. MB-System is an NSF-funded share-ware software application specifically designed to manipulate submarine multibeam sonar data. The MB-System tool 'mbgrid' applied a tight spline tension to the swath sonar data, and interpolated values for nearby cells without data. The resulting 1/3 arc-second ASCII grid was brought into ArcGIS for evaluation and conversion to MHW, and exported as xyz data for surfacing of all of the bathymetric data.

3.3.3 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the 1/3 arc-second Lahaina DEM: in deep water, the NOS survey data have point spacings up to 900 m apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEM due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing 'pre-surface' or grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The NOS hydrographic point data, in xyz format, were combined with the USGS and JALBTCX survey data into a single file, along with points extracted from the NGA coastline—to provide a "zero" buffer along the entire coastline. These point data were then median-averaged using the GMT tool 'blockmedian' to create a 1 arc-second grid 0.05 degrees (~10%) larger than the Lahaina DEM gridding region. The GMT tool 'surface' then applied a tight spline tension to interpolate cells without data values. The GMT grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the coastline (to eliminate data interpolation into land areas). The resulting surface was compared with the original soundings to ensure grid accuracy (e.g., Fig. 11), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 7).

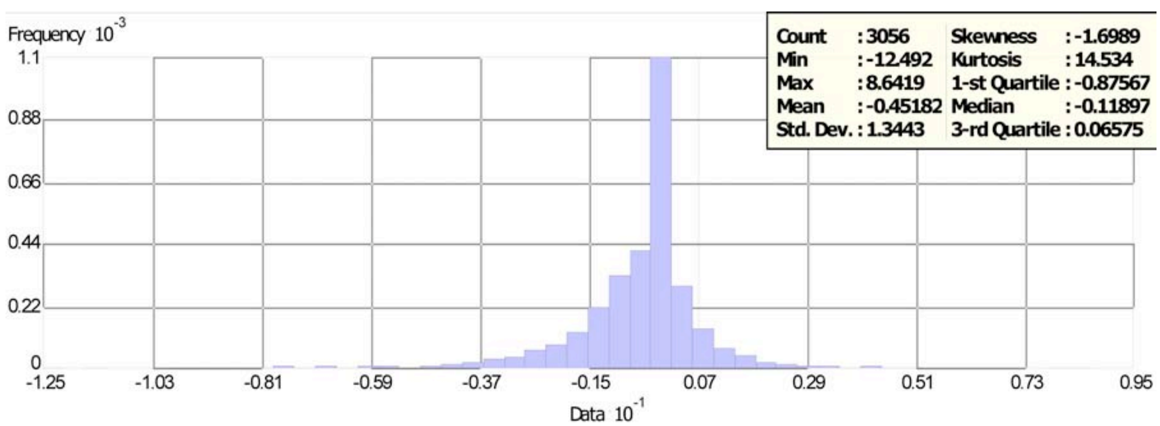

Figure 11. *Histogram of the differences between NOS hydrographic survey H08522 (3,056 points) and the 1 arc-second pre-surfaced bathymetric grid. Discrepancies between survey soundings and the pre-surface grid result from the averaging of several closely spaced soundings.*

3.3.4 Gridding the data with MB-System

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to create the 1/3 arc-second Lahaina DEM. The MB-System tool 'mbgrid' applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 7. Greatest weight was given to the high-resolution coastal bathymetric and topographic LiDAR surveys. Least weight was given to the pre-surfaced 1 arc-second bathymetric grid. The resulting Arc ASCII grids were seamlessly merged in ArcCatalog to create the final 1/3 arc-second Lahaina DEM.

Table 7. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
CSC coastal topographic LiDAR	10000
JALBTCX SHOALS coastal bathymetric LiDAR	10000
USGS multibeam sonar data	1000
USGS multibeam bathymetric DEM	100
USGS NED topographic DEM	100
NOS hydrographic surveys: bathymetric soundings	100
Pre-surfaced bathymetric 1 arc-second grid	1

3.4 Quality Assessment of the DEM

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Lahaina DEM is dependent upon the datasets used to determine corresponding DEM cell values. Topographic features have an estimated accuracy of 1 to 15 meters: CSC coastal LiDAR data have an accuracy of between 1 and 3 meters, NED topography is accurate to within about 15 meters. Bathymetric features are resolved only to within a few tens of meters in deep-water areas (i.e., the southwest corner of the DEM). Shallow, near-coastal regions have an accuracy approaching that of subaerial topographic features. Positional accuracy is limited by: the sparseness of deep-water soundings; potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys; and the observed offset between the USGS raw multibeam data and the USGS bathymetric DEM derived from that multibeam data.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Lahaina DEM is also highly dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy of 0.15 (for CSC coastal LiDAR data) to 7 meters (for NED topography). Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth (~10 meters in the southwest corner of the DEM). Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope maps and 3-D perspectives

ESRI ArcCatalog was used to generate a slope grid from the Lahaina DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 12). The DEM was transformed to UTM Zone 4 coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM (e.g., Fig. 13) was accomplished using ESRI ArcScene. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 1 shows a color image of the 1/3 arc-second Lahaina DEM in its final version

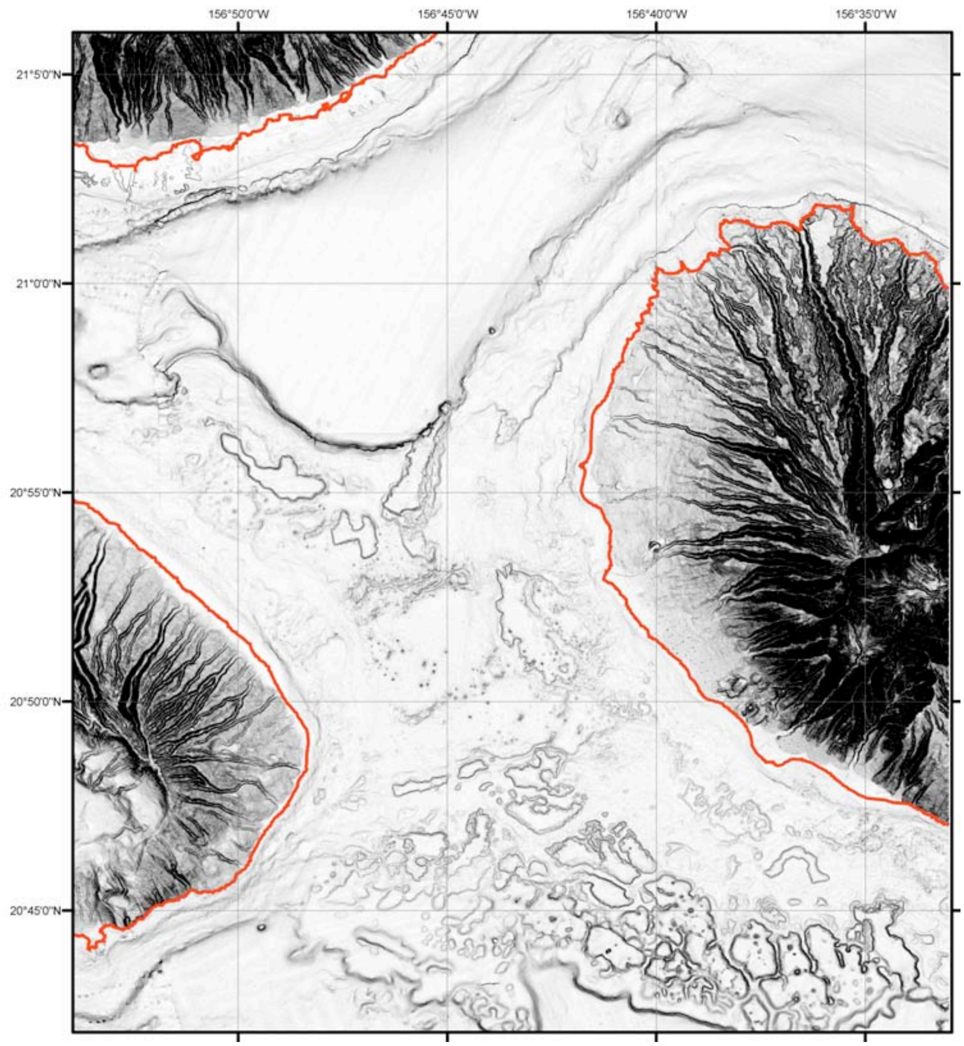

Figure 12. *Slope map of the Lahaina DEM. Flat-lying slopes are white; dark shading denotes steep slopes; NGA coastline in red.*

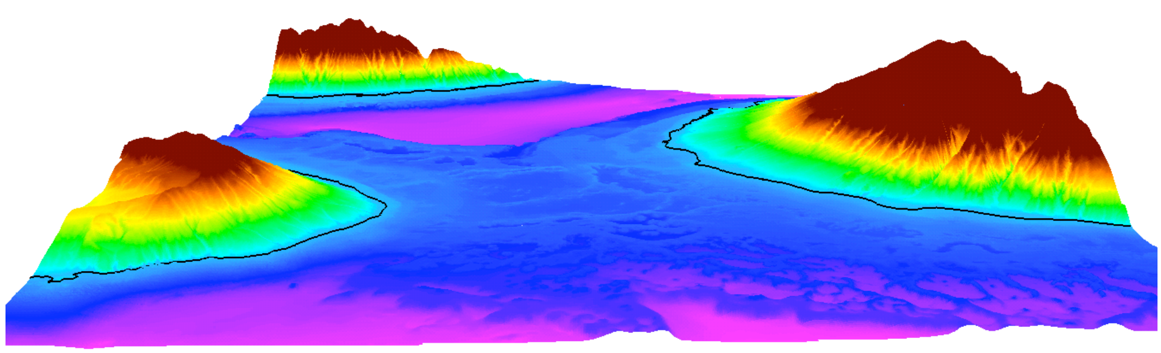

Figure 13. *Perspective view from the south of the Lahaina DEM. NGA coastline in red; vertical exaggeration–times 3.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Lahaina DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the difference between one CSC coastal topographic LiDAR survey file—covering the town of Lahaina—and the Lahaina DEM is shown in Figure 14. Figure 15 shows a comparison between one JALBTCX coastal bathymetric survey—covering the marine region offshore Lahaina—and the Lahaina DEM. Both show close agreement with the DEM, with the exception of areas where closely spaced values contribute to one elevation in the DEM. Significant discrepancies between some data values and the DEM resulted in reevaluation of the source data, further data editing and building of a revised DEM.

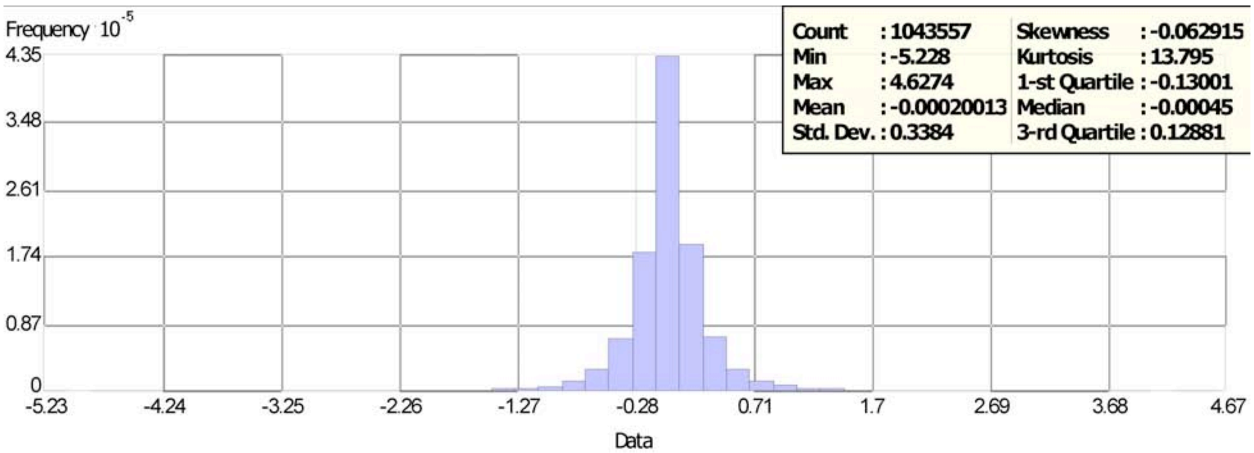

Figure 14. *Histogram of the differences between one file of the CSC coastal topographic LiDAR survey (1,043,557 points) and the Lahaina DEM. The largest discrepancies result from the averaging of many closely spaced elevation values in regions of steep terrain.*

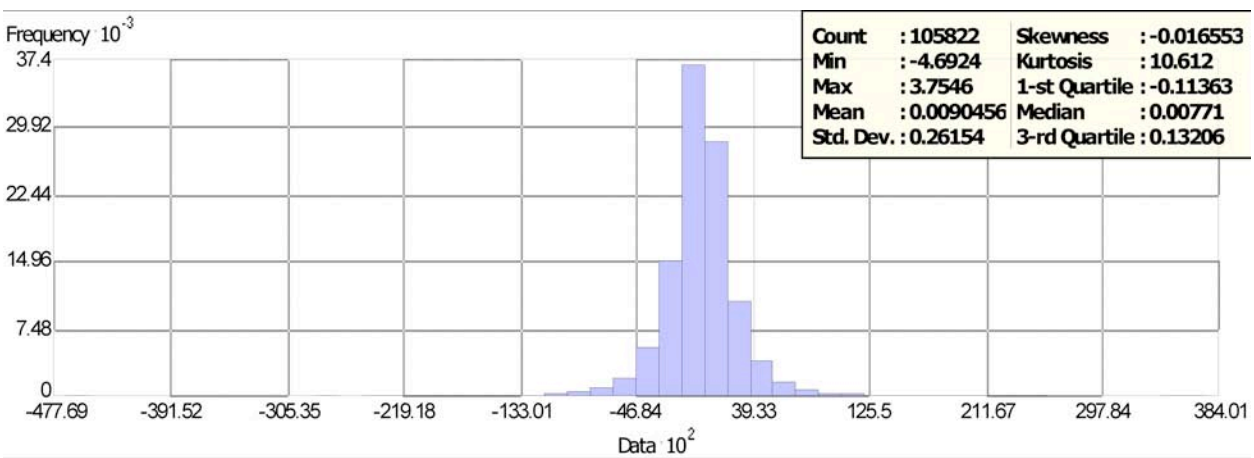

Figure 15. *Histogram of the differences between one file of the JALBTCX coastal bathymetric LiDAR survey (105,822 points) and the Lahaina DEM. The largest discrepancies result from the averaging of several closely spaced elevation values.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 69 NOAA NGS geodetic monuments were extracted from online shape files of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD83 (sub-mm accuracy) and elevations in Local Tidal datums, which is assumed to be equivalent to MSL. Elevations were shifted to MHW vertical datum (see Table 6) for comparison with the Lahaina DEM (see Fig. 17 for monument locations). Differences between the Lahaina DEM and the NGS geodetic monument elevations range from -26 to 15 meters, with a positive value indicating that the DEM elevation value is greater than the monument elevation (Fig. 16). Examination of the monuments with the largest positive offsets from the DEM revealed that the corresponding DEM elevations derive from the USGS NED topographic DEMs. This is especially notable along the southeast coast of Molokai, where NED values of approximately 15 m extend some 30 meters offshore. The largest negative offset occurs where the position and/or elevation of an NGS monument's (TU3194, on the southern coast of Lanai) appears to be incorrect.

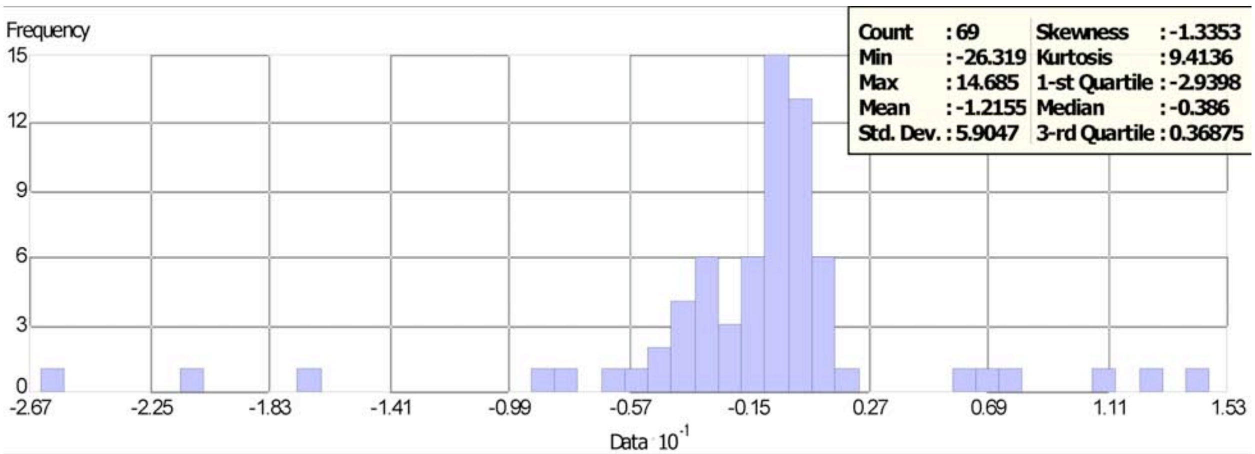

Figure 16. *Histogram of the differences between NGS geodetic monument elevations and the Lahaina DEM.*

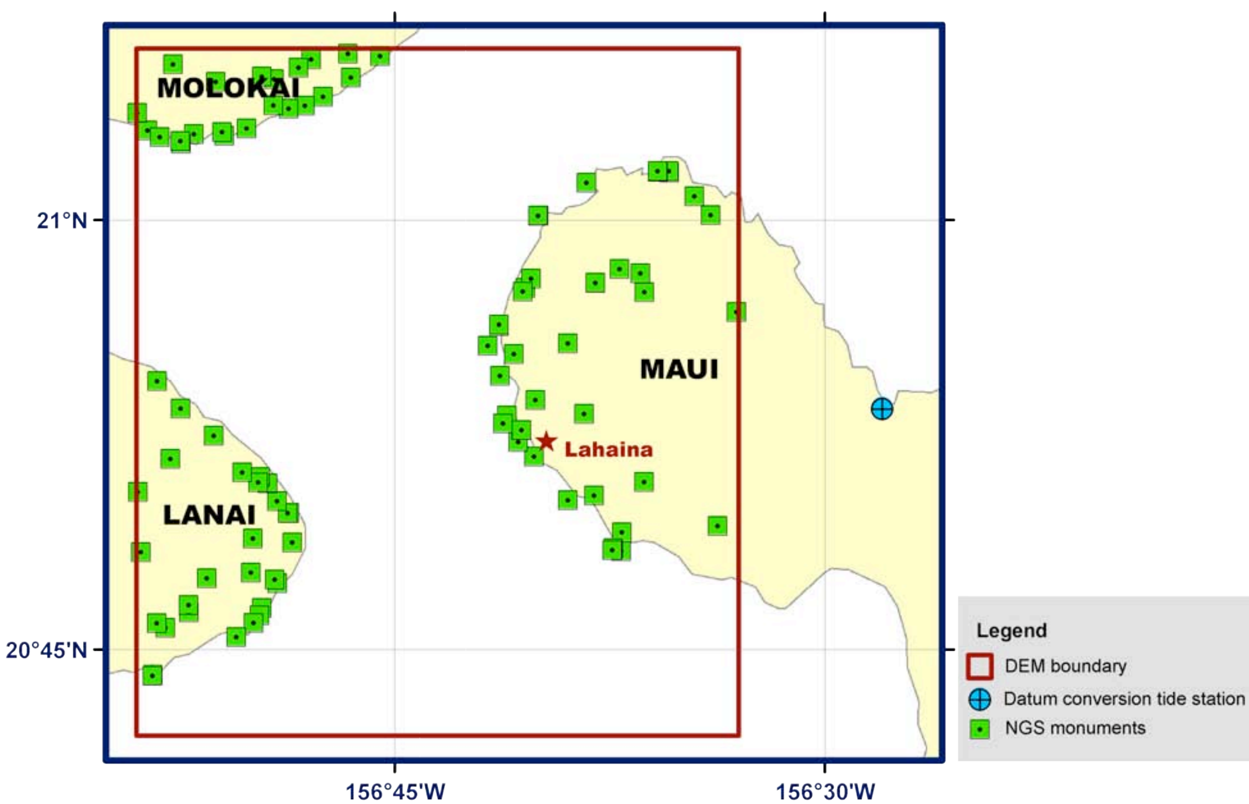

Figure 17. *Location of NGS monuments and NOAA tide stations in the Lahaina region. Circle locates tide station used to convert between vertical datums; NGS monument elevations were used to evaluate the Lahaina DEM.*

4. Summary and Conclusions

A topographic–bathymetric digital elevation model of the Lahaina, Hawaii region, with cell spacing of 1/3 arc-second, was developed for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. The best available digital data from U.S. federal agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT, and MB-System software.

Recommendations to improve the Lahaina DEM, based on NGDC's research and analysis, are listed below:

- Conduct topographic LiDAR surveys along the coasts of Molokai and Lanai.
- Obtain all of the raw multibeam files of the USGS bathymetric survey around Maui or rectify the discrepancies between the USGS raw multibeam and the derived USGS bathymetric DEM.

5. Acknowledgments

The creation of the Lahaina DEM was funded by the NOAA, Pacific Marine Environmental Laboratory. The authors thank Chris Chamberlin and Vasily Titov (PMEL), Darcee Killpack (NOAA Pacific Services Center), and Jeff Lillycrop (USACE). The USGS raw multibeam files had been previously shared with B. Eakins by Jim Gardner (USGS), also much appreciated.

6. References

Nautical Chart #19347, 18th Edition, 2005. Channels between Molokai, Maui, Lanai and Kahoolawe. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #19348, 8th Edition, 2003. Approaches to Lahaina. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

Electronic Navigational Chart Data Handler for ArcView, developed by NOAA Coastal Services Center, http://www.csc.noaa.gov/products/enc/

FME 2006 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

GEODAS v. 5 – Geophysical Data System, shareware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.1.4 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/